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DEVELOPMENT, VIBRATION, AND THERMAL CHARACTERIZATION OF A STEADY OPERATING PULSED POWER SYSTEM FOR FRC THRUSTERS

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ABSTRACT

A steady operating pulsed power system has been developed for advanced electromagnetic propulsion systems. This PPU has been developed for advanced electric propulsion systems which use inductive loads to provided electromagnetic forces which accelerate a plasma. The Electrodeless Lorentz Force (ELF) Thruster is a revolutionary electric propulsion thruster and power processing system that will allow a significant decrease in system mass and increase lifetime over traditional 500-10000 W propulsion systems. The ELF employs a Rotating Magnetic Field (RMF) to produce large plasma currents inside a conical thruster creating a field-reversed configuration (FRC) plasmoid that is magnetically isolated from the thruster walls.

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INTRODUCTION

The Electrodeless Lorentz Force Thruster (ELF) represents a new thruster technology that is being developed at MSNW and has the capability to address the demanding combined requirements of high specific power, high efficiency, a large Isp range, and T/P in a single device. ELF technology has demonstrated the ability to ionize, electromagnetically accelerate, and eject a broad range of complex and chemically-reactive molecular gases, including monopropellants. The highly scalable ELF represents a dramatic advancement for Electric Propulsion technology has the potential to dramatically exceed the operational range of existing electric propulsion systems in power density, power throttling, and propellant choice for 1 kW to 1 MW electric propulsion thrusters.

ELF technology creates a high-density, magnetized plasmoid known as a Field Reversed Configuration (FRC) using external RF antennas that produce a Rotating Magnetic Field (RMF) which is transverse to the thruster axis. The synchronous motion of the electrons magnetized in this field produce a large azimuthal current that, when driven in a direction opposite to that flowing in the external solenoid, reverses the magnetic field inside the plasma forming a closed magnetic

field plasmoid (the FRC). The large FRC plasma current, together with the radial magnetic field, result in a $J_\theta xB_r$ force that rapidly accelerates and expels the FRC propellant creating thrust.

A Phase II DARPA program developed a 1 kW FRC-based thruster that would be capable of demonstrating this technology in orbit. The effort will result in a space-rateable pulsed power circuit design, thruster body thermal design, and flight PI design. To this end, a proto-flight Pulse Power Unit (PPU) has been designed, fabricated and tested to survey and characterize it suitability for operation in the space environment contributing to the goal of a space rated and operational ELF system. The proto-flight 1kW and 5kW class PPUs underwent environmental testing for vibration, thermal, and radiated EMI characterization.

ELECTRONICS TOPOLOGY

The PPU is a modular component of the ELF. The fundamental topology of the PPU is that of a boost converter coupled with a low Q, LC oscillator. With this arrangement a current pulse across the inductor of the pulse charging assembly provides a charge voltage for the capacitor bank or the PPU. The charge is retained by the blocking diode of the boost converter. The PPU capacitor is then discharged across the drive antenna of the ELF which is a low Q circuit allowing for several cycles of oscillation in the LC circuit with the inductance being provided by the thruster antenna. The discharge is controlled by a high side IGBT switch. This switch is high side in order to maintain a neutral voltage on the thruster antenna when inactive. The low impedance transmission line connecting the capacitor and switch of the PPU module to the thruster antenna is comprised of multiple parallel coaxial cables. Figure 1 is a diagram for the basic electronics block for the PPU.

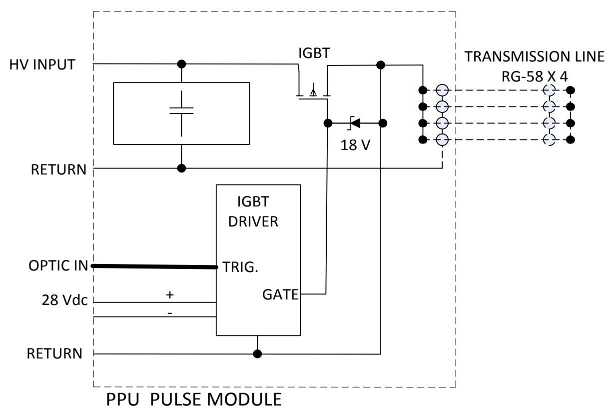


Figure 1. PPU Module Block Diagram

A typical electrical configuration for operating the PPU is shown in Figure 2. Here the pulse charge assembly and the 28 Vdc isolated power supply are external to the PPU. The high current power supply will operate at between 40 and 100 volts and result in as much as a 1600 volt charge of the PPU capacitor bank, depending on specific operating requirements and configurations. The power drawn by the ELF antenna / PPU system is determined by the energy per pulse multiplied by the number of pulses per second.

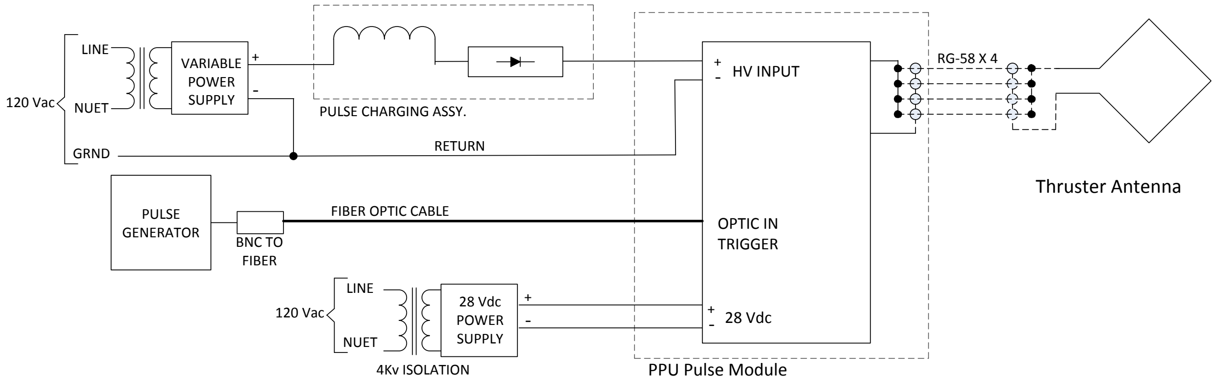


Figure 2. ELF Antenna Block Diagram

ENCLOSURES

As with all satellite structures, the driving design requirements are to maximize the stiffness-to weight ratio for the enclosure where mass is the primary design driver followed closely by reliability. For responsive and experimental space missions, time and cost are also significant design drivers.

To insure reliability, the enclosure must be able to survive high vibration, acoustic, and shock loads during launch, to provide adequate thermal management, to minimize deflection, and to provide dimensional stability for internal components. Modularity is achieved through the use of mounting and wiring devices that allow for installation and removal of the unit without the need to open the enclosure. These designs were intended to allow highly parallelized feed assemblies as well as in-situ conformal coating and potting. At this time the designs have not been mass optimized, but will be in the next design iteration in response to the results of EMI, Vibe, and Thermal Testing.

The current design uses a feed-through plate to pass through input electrical connections. This design will be replaced with an aluminum plate with circular connectors for electrical and fiber optic connections. The output will continue to be implemented using feed-throughs. For this effort, two boxes were designed, fabricated and tested. The size of these units is based on Joules per pulse. The smaller PPU provides roughly 1 Joule per pulse while the larger PPU provides 6 Joules per pulse. These PPUs have been designated as J1 and J6. With this nomenclature, J stands for Joules. The block diagram for the J1 enclosure is essentially identical to that shown in Figure 1 as this unit contains a single PPU module. The block diagram for the J6 enclosure is shown in Figure 3 with 6 PPU modules connected in parallel.

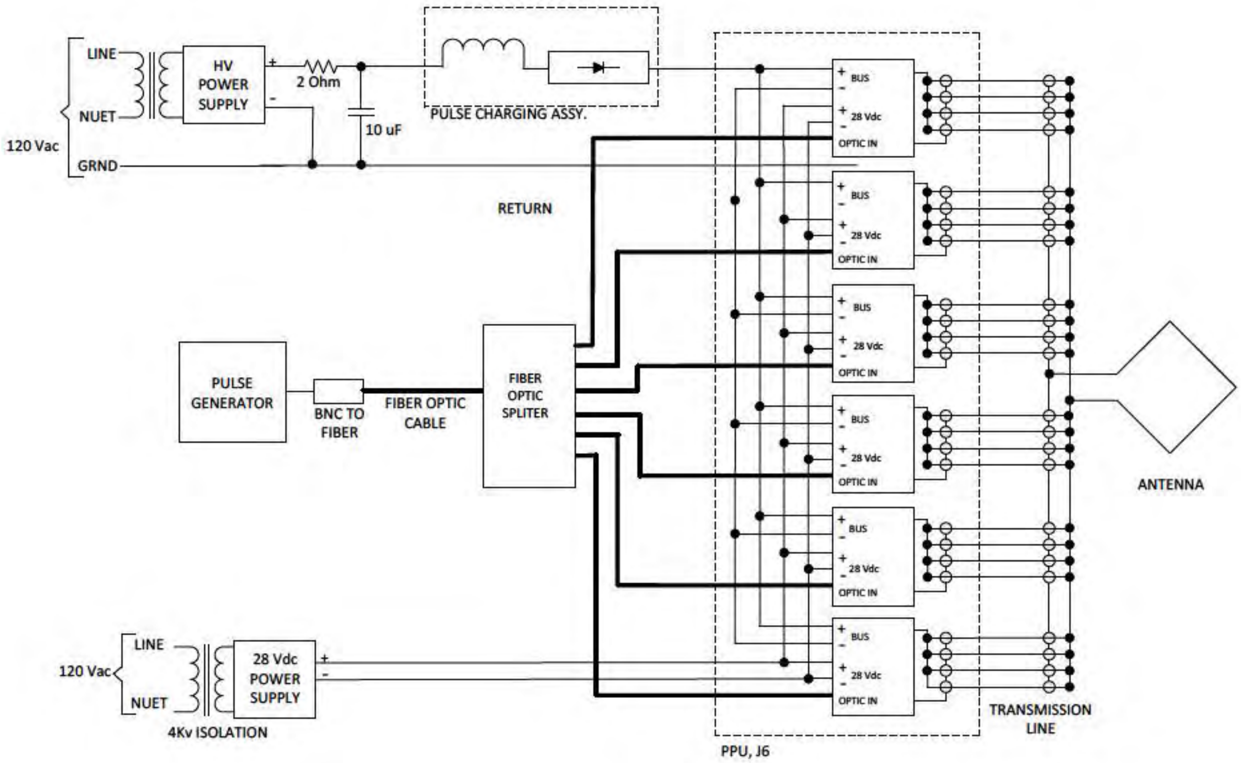


Figure 3. J6 PPU Configuration

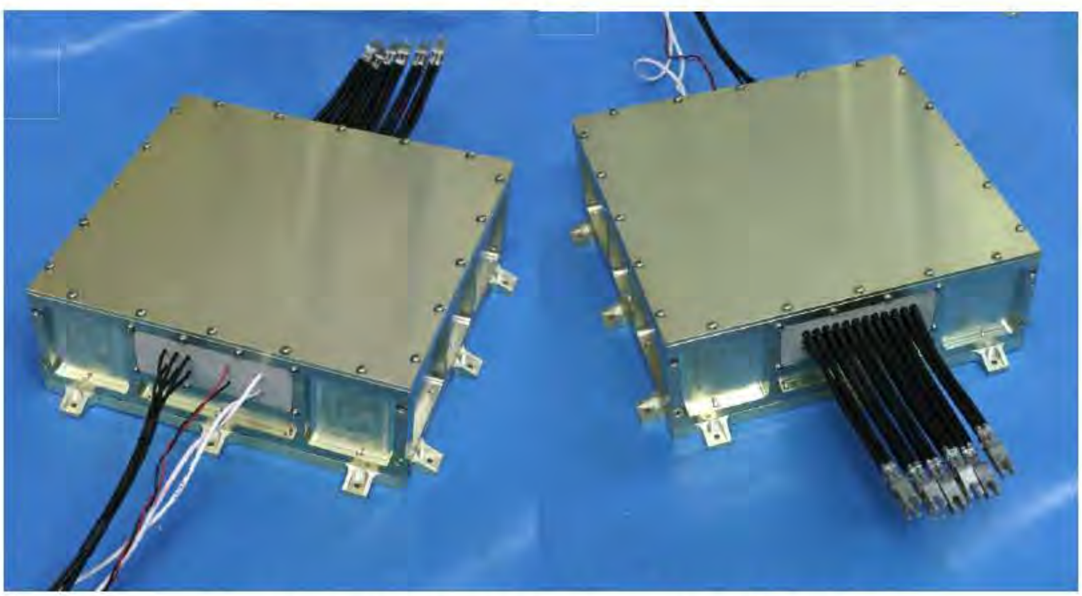


Figure 4. The input and output side of the J6 PPU

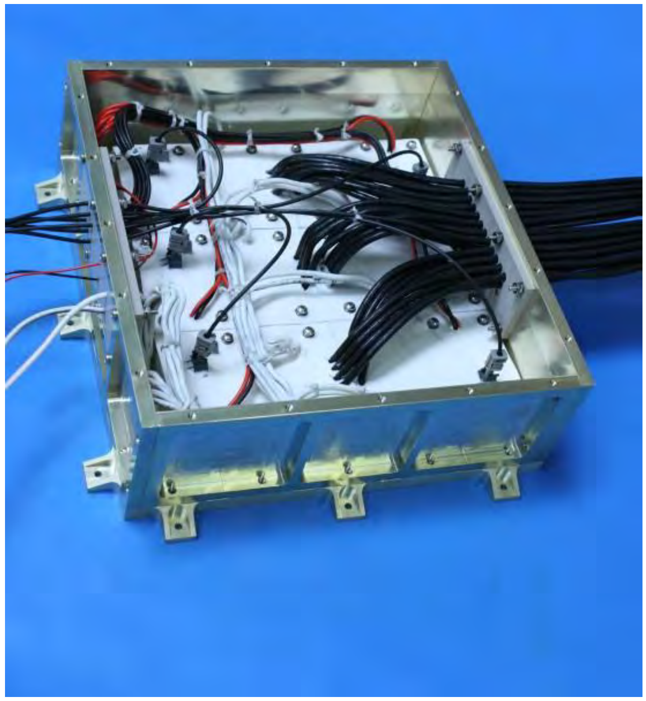


Figure 5. J6 PPU with cover removed

Vibration Testing Results

RATIONALE FOR PROTO-QUALIFICATION VIBRATION TESTING

The purpose of this vibration testing spacecraft hardware is to:

1. Demonstrate the ability of the hardware to successfully operate after being exposed to the harsh launch vibration environment.
2. Uncover workmanship flaws such as loose fasteners or weak solder joints.

Vibration testing may also be used to validate FEA modal analysis predictions of first-mode structural resonance frequencies.

Based on the two above-listed purposes, the resulting success criteria for the vibration test are:

1. Verify PPU functionality is not degraded by exposure to vibration.
2. Verify PPU mechanical integrity has not degraded by confirming the resonant frequencies for each axis have not changed or shifted after exposure to random vibration and high-level sinusoidal vibration testing.

TEST METHODOLOGY OVERVIEW

The testing approach was developed in a partnership between MSNW, Altius Space Systems, and AFRL. The vibration testing regime for each PPU consisted of performing the following tests on each of three orthogonal axes:

1. A low-level sine sweep test to measure PPU resonant frequencies.
2. A random vibration test to test PPU workmanship and expose the PPU to simulated launch vibration loads.
3. A high-level sine sweep test to expose the PPU to simulated low-frequency launch vibration loads, and launch accelerations.
4. A second low-level sine sweep test to verify no structural damage to the PPU.

After each test, 1 through 4, a limited electrical functionality test was performed to verify PPU functionality. Because the spacecraft and launch vehicle that the PPU will be flown on are currently unknown, GSFC-STD-7000A provides a generalized random vibration testing level specification that can be used. Additionally, the EELV Secondary Payload Adapter Rideshare User's Guide (ESPA RUG) also provides a similar vibration testing level specification. These two specifications are described below in both tabular form (Figure 6) and in chart form (Figure 7). These specifications provide the acceleration spectral density in g^2/Hz versus frequency.

GSFC-STD-7000A (Table 2.4-3)	
Frequency (Hz)	ASD (g^2/Hz)
20	.026
50	.16
800	.16
2000	.026

ESPA RUG (Figure 3.2.3.1-1)	
Frequency (Hz)	ASD (g^2/Hz)
20	0.01
50	0.35
70	0.35
100	0.2
200	0.2
250	0.2
400	0.07
900	0.07
2000	0.01

Figure 6. Vibration qualification standards investigated

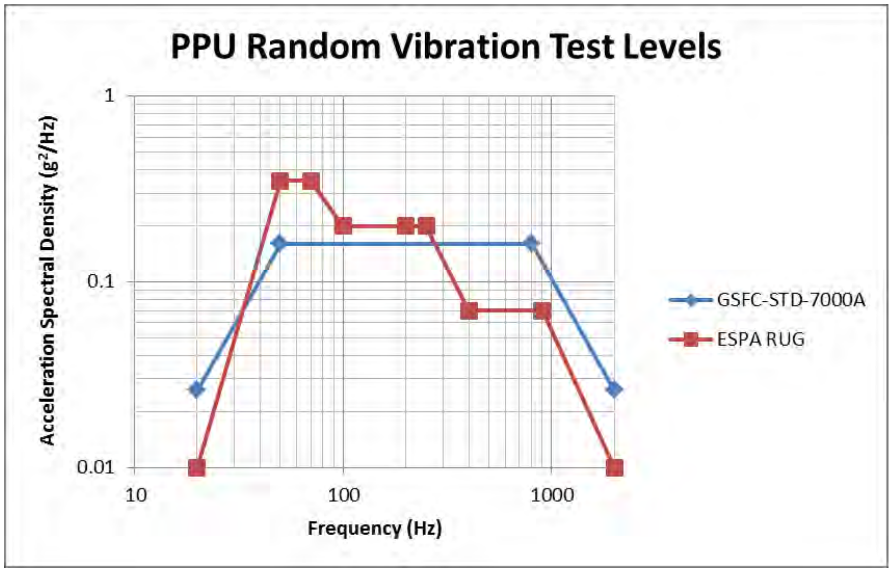


Figure 7. Vibration qualification standards investigated

The testing levels provided by the ESPA RUG are for spacecraft flying on an ESPA adapter on one of the two EELV vehicles, Atlas V or Delta-IV. The GSFC-STD-7000A test levels are more generalized for other launch vehicles. While the ESPA RUG data has a higher ASD at low frequencies, the GSFC-STD-7000A test levels actually have a higher G_{RMS} value (14.1 vs. 11.3), due to the higher ASD levels at high frequencies. The G_{RMS} value is the square root of the area under the curve shown in Figure 7. In order to accommodate all potential launch vehicles, these testing limits are more launch vehicle agnostic, but the G_{RMS} level based on combining these limits will be slightly higher than the GSFC-STD-7000A value.

Frequency (Hz)	ASD (g^2/Hz)
20	0.026
50	0.35
70	0.35
100	0.2
200	0.2
250	0.2
280	0.16
800	0.16
2000	0.026

Figure 8. Combined vibration qualification standards

TEST HARDWARE

The test hardware included:

1. The J1 and J6 PPU test articles
2. An adapter plate for mechanical mounting to the shaker unit.
3. The limited functionality testing cart including simulated ELF thruster coils, power supplies, triggering systems, cables, and an oscilloscope for measuring electrical outputs
4. Cameras for photographing the configuration of the test articles prior to testing a given axis, and for video recording test behavior during random vibration and high-level sinusoidal vibration testing.
5. The Vibration Test Facility shaker table, shaker cube, input and response accelerometers, and data acquisition system

Figure 9 and Figure 10 show an example of the vibration test setup and limited functionality electrical test setup used for the vibration testing.

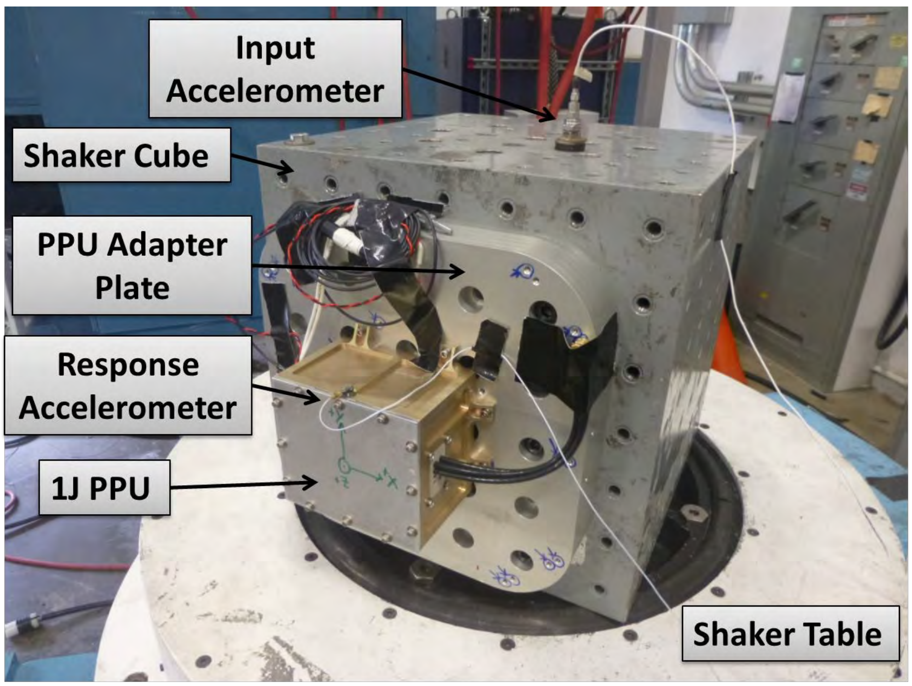


Figure 9. J1 PPU on Shaker Table Before Y+ Axis Testing

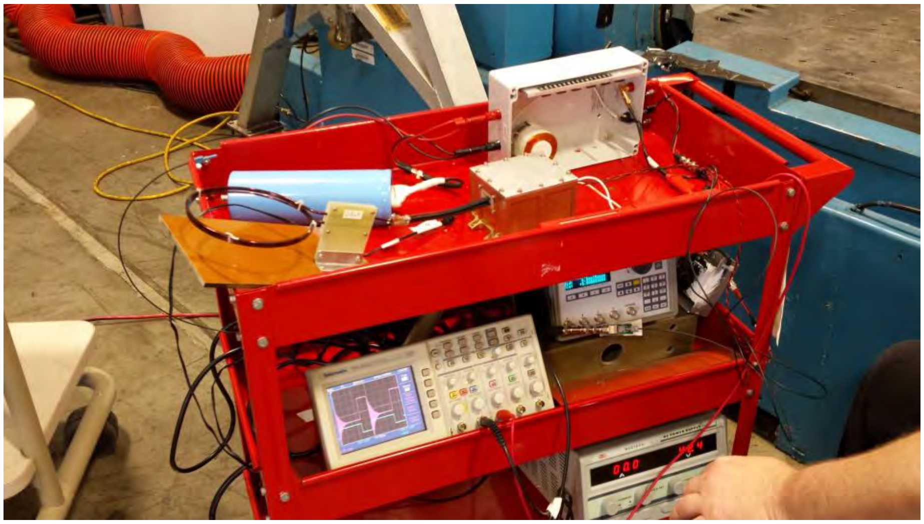


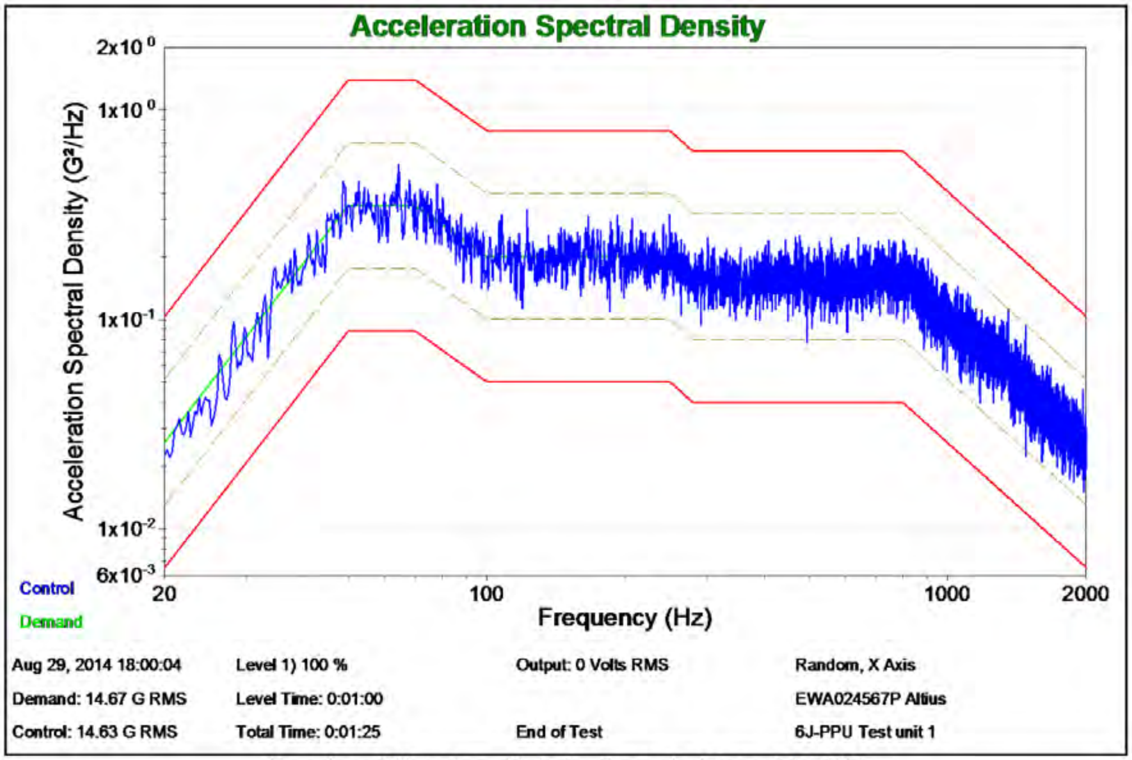
Figure 10. J1 PPU on the Limited Functionality Test Cart

DEVIATIONS FROM THE ORIGINAL PLAN

There were only a few deviations from the original plan proposed by Altius to MSNW:

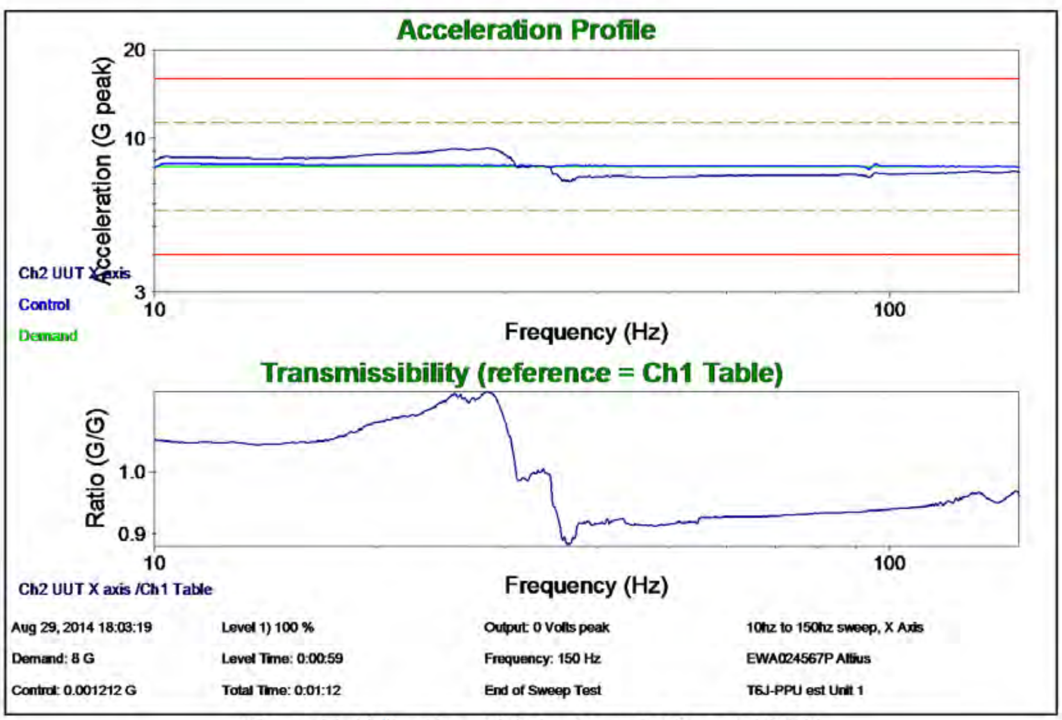
1. The original plan called for bringing the PPU back to MSNW after each axis of testing was completed for functionality testing at MSNW facilities. The test cart shown above in Figure 10 was portable enabling functionality testing to be performed at Element facilities, greatly expediting the testing process.
2. The original plan was to only test the J1 PPU, but the time savings facilitated by the portable test cart enabled testing both the J1 and the J6 PPU.
3. High-level sinusoidal sweep testing was originally not recommended as part of the vibration testing, as such tests are often driven by a combined loads analysis that would require knowing what launch vehicle and spacecraft the hardware would be flying on. However, based on recommendations from Ball Aerospace an 8G test from 5-150Hz was recommended as a good bounding case that would cover most typical launch environments.
4. The High-Level Sinusoidal Sweep test was originally planned to be an 8G test sweeping from 5-150Hz, with a displacement-limited ramp from 5Hz to approximately 18Hz. Due to limitations of shaker table displacement amplitude, the frequency range 5-10 Hz was removed from the testing frequency range. The test range used is 10-150Hz.
5. For the low-level pre- and post- sinusoidal sweeps, the acceleration level was increased from 0.25 to 0.5G. This was due to control accelerometer noise causing shaker table control system shutdowns during testing.

Figure 11 shows the total tested spectrum. Figures 12-13 show the results from X axis testing. Y axis was essentially identical. Figure 14-16 show Z axis testing.



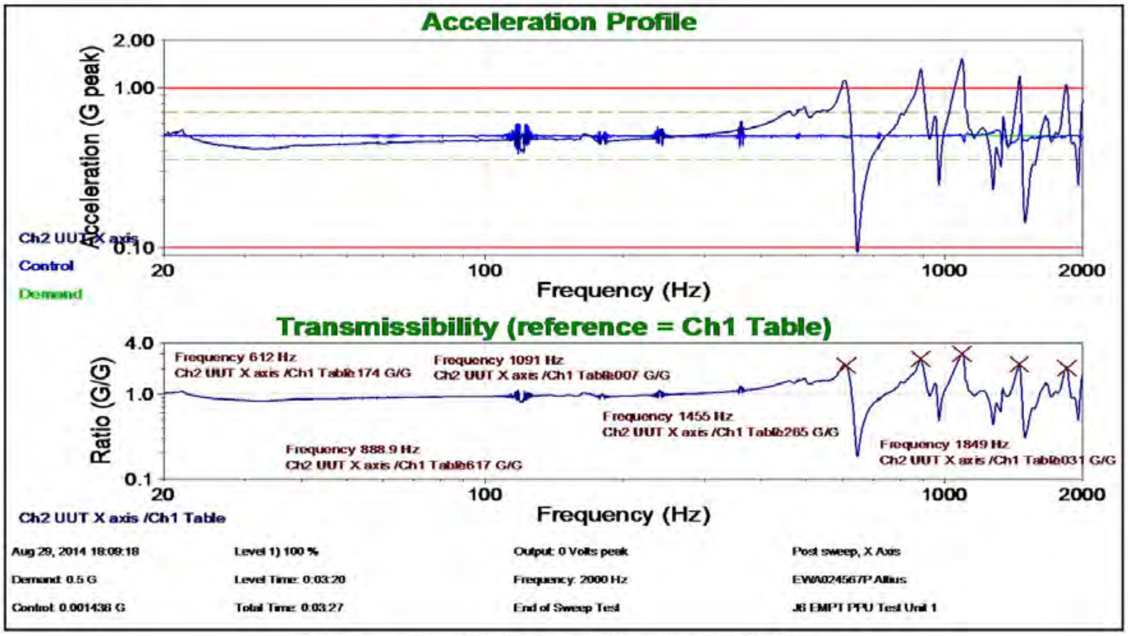
Random Vibration, X Axis, Sample Type 6J-PPU

Figure 11. J6 PPU Vibration Testing Input Profile for all axes



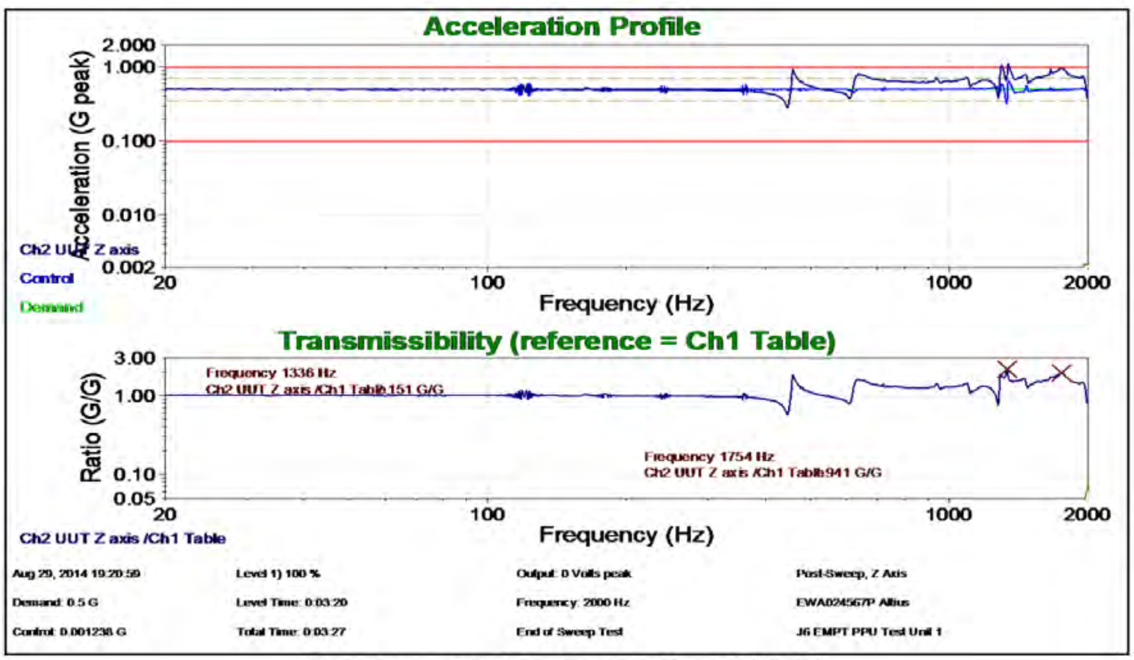
Sinusoidal Vibration, X Axis, Sample Type 6J-PPU

Figure 12. J6 PPU Vibration Testing Results - X Axis



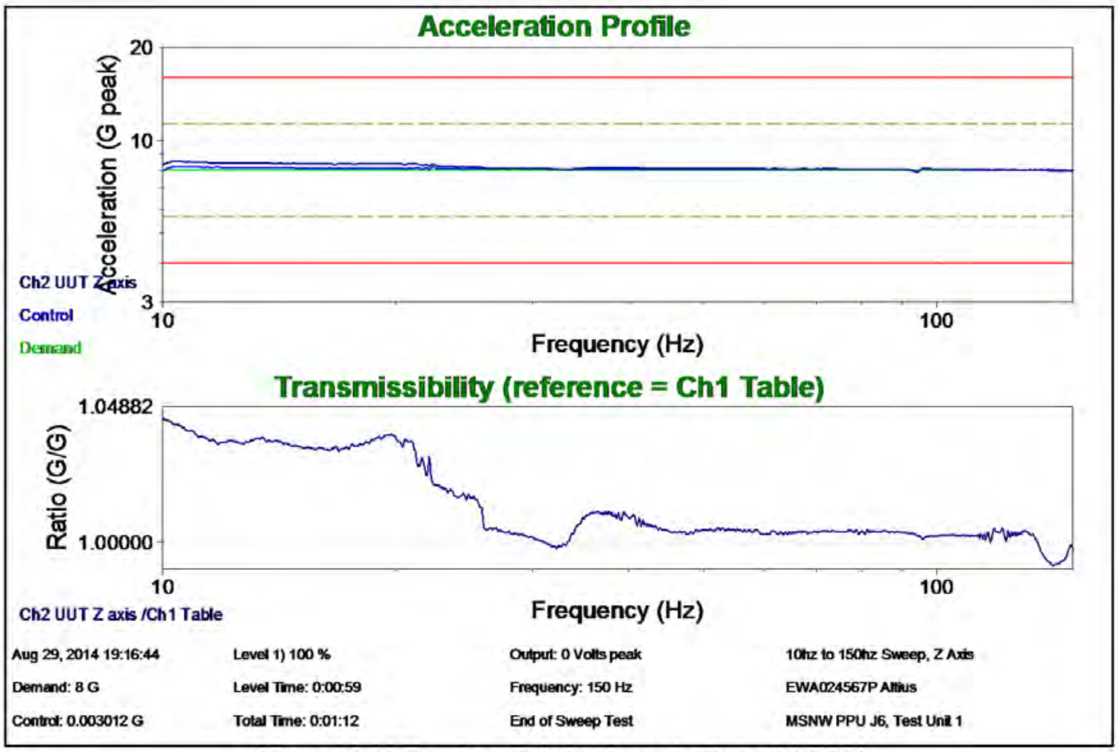
Post-Sweep, X Axis, Sample Type 6J-PPU

Figure 13. J6 PPU Vibration Testing Results - X Axis



Post-Sweep, Z Axis, Sample Type 6J-PPU

Figure 14. J6 PPU Vibration Testing Results - Z Axis



Sinusoidal Vibration, Z Axis, Sample Type 6J-PPU

Figure 15. J6 PPU Vibration Testing Results - Z Axis

RESULTS

Key results from these tests were that:

1. The resonant frequencies for the two PPUs did not shift after random vibration testing and high-level sinusoidal sweep testing for any of the axes tested. This indicates no mechanical failures were caused by testing, and testing did not uncover any workmanship errors in spite of exposing the PPUs to vibration levels in excess of what is expected for flight on any of the launchers covered by the GSFC-7000A (GEVS) or EELV ESPA RUG standards.
2. The boxes retained normal functionality after exposure to vibration test environments. The electrical performance had not noticeably shifted from the tests performed before the vibration testing.

While no modal analysis was performed to predict the first-mode frequencies of the boxes, the measured resonant frequencies were all greater than 600Hz, which should be more than adequate for space electronics enclosures. The test results indicate the enclosures are built more robustly than is required for the application. This provides weight margins for future revisions of the PPU enclosure design.

Based on the success criteria of:

1. Demonstrate the ability of the hardware to successfully operate after being exposed to the harsh launch vibration environment.
2. Uncover workmanship flaws such as loose fasteners or weak solder joints.

Both the J1 and J6 PPU proto-flight test articles successfully completed testing on three orthogonal axes, and can be considered acceptable for flight from a vibration test perspective.

THERMAL TESTING

Thermal-Vac testing demonstrates the ability of the PPU to perform in an environment which simulates the temperature and vacuum of the LEO environment for the spacecraft and PPU. This testing includes thermal cycling testing.

Test objectives for thermal-vac testing included the following:

1. Perform thermal-vac cycles to simulate LEO orbital heating changes
2. Ensure the PPU will start and operate after min/max temperature soaks
3. Acquire data that will verify the thermal model
4. Measure PPU performance at extremes of input voltage and temperature
5. Measure PPU performance changes before, during, and after testing

The PPU thermal-vac testing approach was based on MIL-STD-1540B, NASA PRACTICE NO. PD-ED-1202, and the ESPA RUG.

The following test parameter limits and assumptions apply to all tests described in this section:

1. The PPU enclosure used flight surface finishes
2. The PPU was mounted on a thermally controlled heat sink or baseplate in a thermally and mechanically-similar manner to how the PPU is intended to be mounted in the spacecraft
3. Temperature stability is defined as when the PPU temperature rate of change is <1°C/min
4. In Year 1 these tests were performed in air, albeit with raised baseplate temperatures to simulate the vacuum and spacecraft environment.

THERMAL CYCLE TESTING

Thermal cycle testing was tested as follows:

1. The cycle starts with the PPU powered-off, and the baseplate temperature held at 20°C long enough for the PPU internal temperature to stabilize.
2. The PPU was powered-on at a constant input power as described in the following tests.
3. With the PPU operating, the temperature of the baseplate was increased to the upper temperature limit (50°C).
4. After the PPU's temperature has stabilized, the baseplate should was held at the upper temperature limit for one hour.
5. After one hour of operations at the upper temperature limit, the PPU was powered-off, and then restarted once electrical circuits have been discharged, and an electrical Limited Performance Test (LPT) should then be performed on the PPU.

J6 TESTING SETUP

The J6 5 kW PPU was used for the thermal testing in Year 1. A water cooled load was developed to simulate the loaded plasma condition of an FRC thruster. This inductive antenna had a fiberglass electrical insulator connected to a stainless steel cylindrical inductive load. The inductive load was cooled with 7 GPM of 30 C water. The copper, uninsulated inductive load was 6 turns with a Q of 64 and yielded a final operational RMF frequency of 213 kHz and a loaded effective Q of 8.5. For a 2.5 kW input power this then is approximately 2.19 kW deposited into the load and an effective PPU efficiency of 88%. Shown in Figure 16 is the complete test setup with standard pulse charging network, PPU enclosure, thermocouples, water cooled load, and heated base plate.

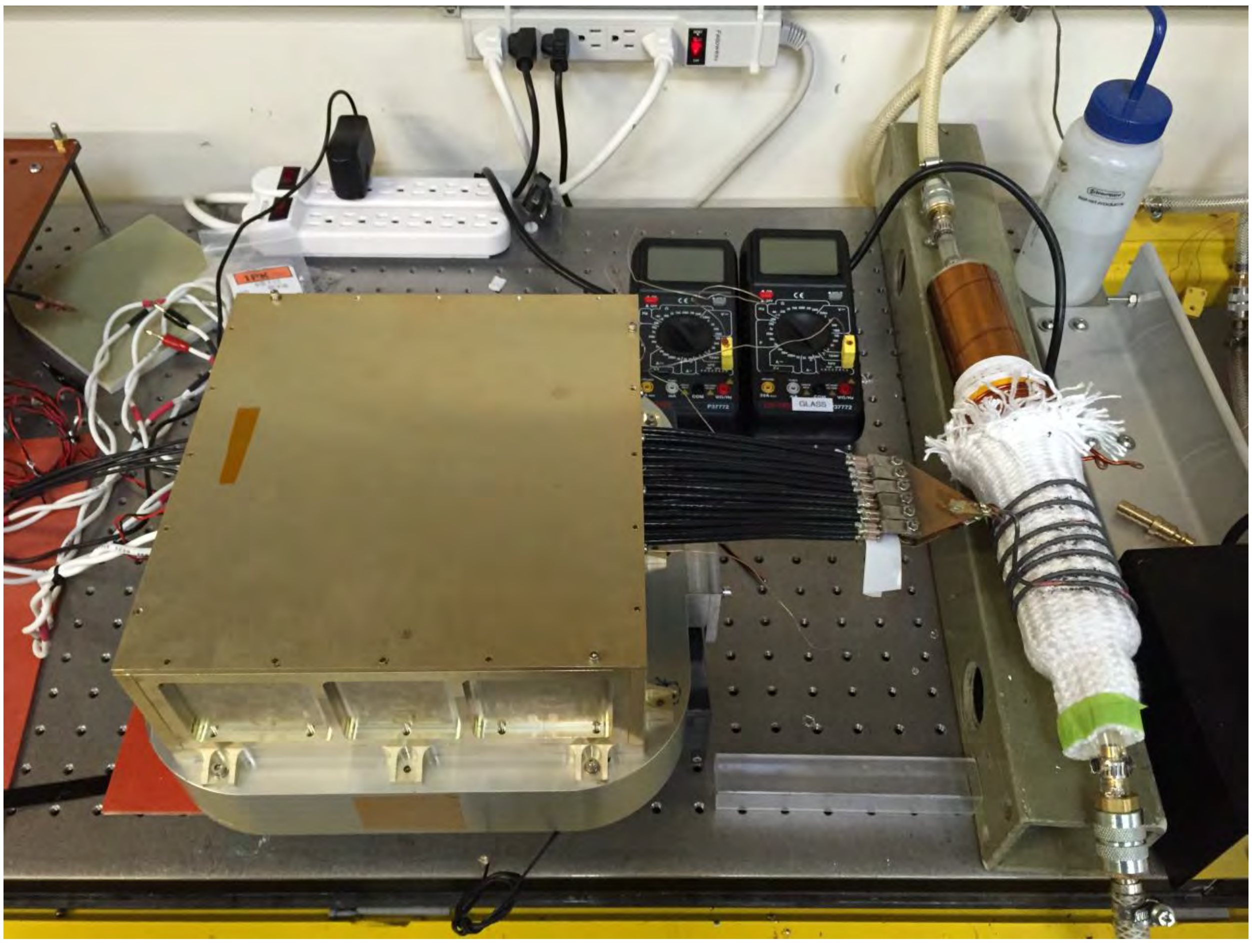


Figure 16. Photograph of the fully assembled J6 Thermal Test Setup

The base plate was heated with a silicon electrical heater an and input of 0-500 Watts. The thruster PPU was operated at 2.5 kW, with a 213 kHz RMF frequency, repetition rate of 4.5 kHz, and average DC power supply at 192 V and 12.9 Amps. Thermocouples were place at three locations, below the IGBT cathode pad, the bottom of the enclosure, and on the cooled load itself. In addition, a thermal imaging camera was used to take photographs of the resulting thermal profiles during heating.

THERMAL CHARACTERIZATION RESULTS

Figure 17 through Figure 21 show the early characterization results of this PPU. In these tests the test fixture was isolated from the environment (via conduction) but did have radiation and convection. In these tests external heat was not required to operate the PPU above 40 °C. Shown in Figure 11 are the temperature increases for various components. It can be seen that the IGBTs have an average of 30 degree thermal increase over the enclosure and test fixture. Various components of the operational electronics (TBD by various spacecraft design) experience significant heating. At the conclusion of this test, a standard functional test was performed and met required specifications. In Year 2, elevated thermal testing and vacuum testing will be performed.

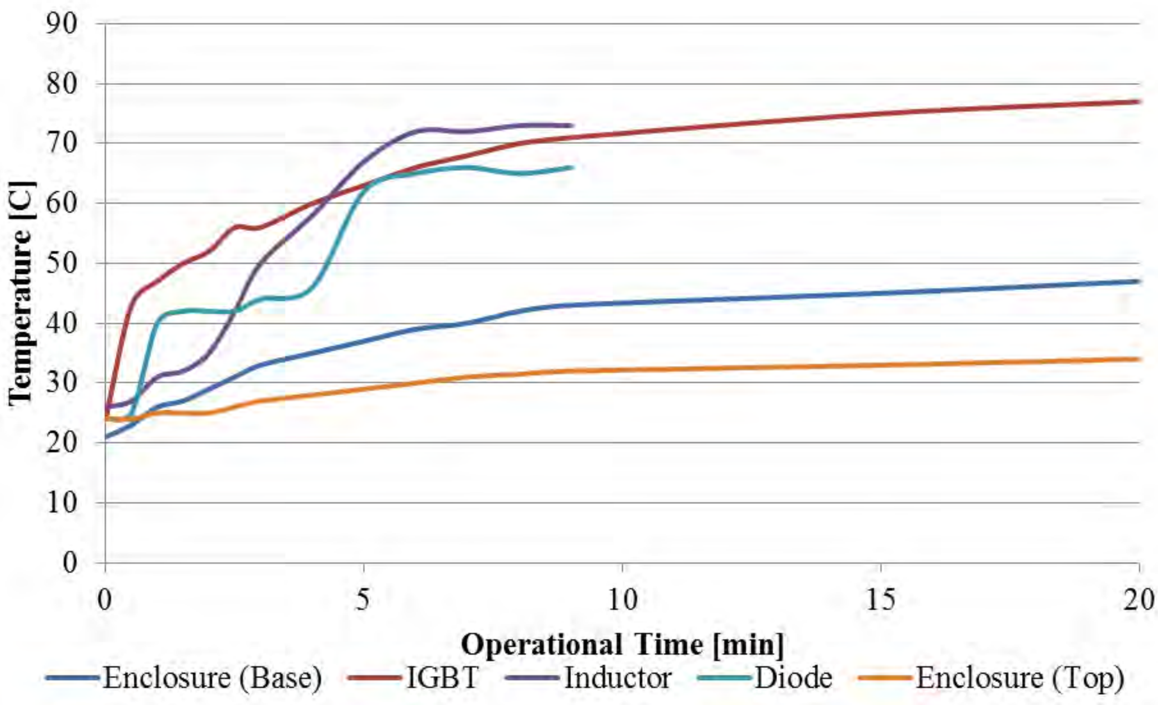


Figure 17. Heating of the J6 assembly without additional heat.

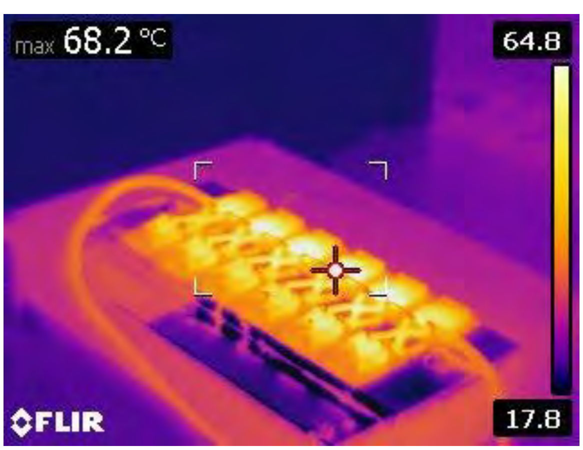


Figure 18. Thermal image of pulse charging diodes

Figure 19. Thermal image of the the enclosure without the lid.

Figure 20. Thermal image closed enclosure and pulse charging diode and inductor.

Figure 21. Thermal image of the inductive plasma simulator.

CONCLUSIONS OF FRC PPU DEVELOPMENT

A set of PPU enclosures were developed for 1 kW (J1) and 5 kW (J6) RMF PPU units. These enclosures are flight-like and allow early thermal and vibration characterization and testing. The tested enclosures met all requirements in the qualification specifications and accounted for structural, thermal, mounting, and coating requirements.

Both the 1J and J6 PPU proto-flight articles successfully passed the suite of vibration tests, which were based on the NASA GSFC-7000A (GEVS) standard. The resonant frequencies of the PPUs were stable after testing in excess of what is expected for flight on any of the launchers covered by the GSFC-7000A (GEVS) or EELV ESPA RUG standards. The pre- and post-test limited performance testing was successfully validated. These two results indicate that the 1J and J6 PPUs successfully passed vibration proto-qualification testing, and should be considered adequately qualified for flight demonstration, from a vibration testing standpoint.

A thermal validation testing was performed during this program period. In these tests the PPUs were operated at 45 C. Testing used a water cooled inductive load and an uncooled baseplate. Elevated temperature and the limited performance validation before and after testing showed that the enclosure and PPU are rated for a 5 kW PPU unit.

In conclusion, the first year of proto-flight qualification testing was successfully completed. In future investigations steps will be taken to further reduce PPU mass, perform more detailed thermal modeling, increase PPU electronics efficiency, and perform external EMI qualification.

ACKNOWLEDGMENTS

MSNW would like to thank the Defense Advanced Projects Agency and Small Business Innovative Research programs which supported this research effort, particularly the program manager for this program, Dr. Jess Sponable.

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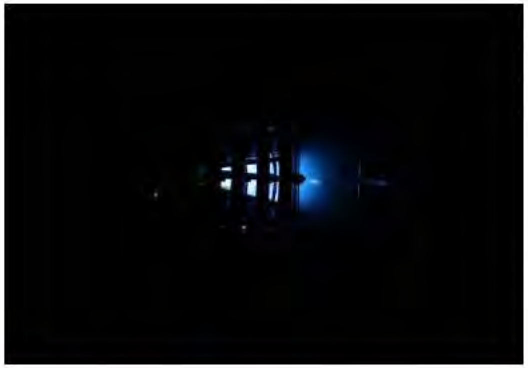
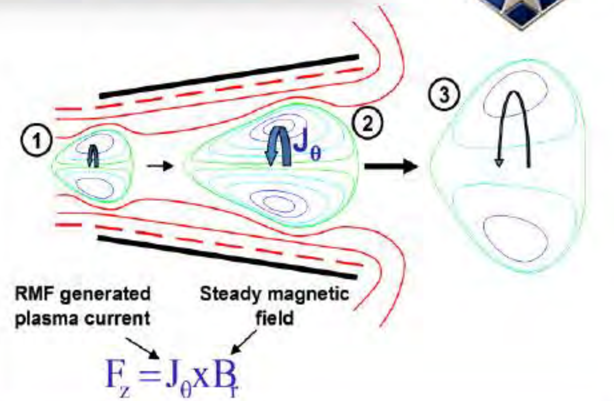
Electrodeless Lorentz Force Thruster

ELF-90 Thruster:

- 200-3000 Watt FRC thruster (0.2-3 Joule)
- Long-life, electrodeless 1 kW-class thruster
- EMPT operates on any gaseous propellant

EMPT forms and accelerates Xenon Field Reverse Configuration Plasmoids with Rotating Magnetic Field Formation



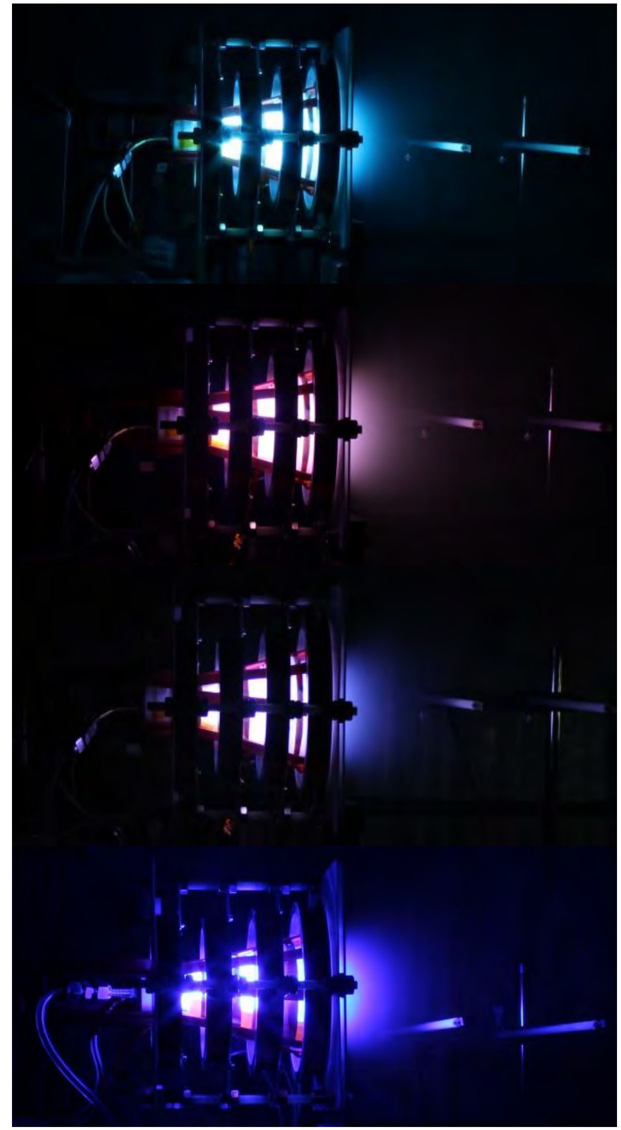


First Demonstration of FRC formation at <1 Joule
First Demonstration of Steady Operation (1E9 FRCs)

- **Plasmoid Achieved 1000-6000s Isp in Xenon, Hydrazine, Martian Air, Water**
- **Revolutionary step in both lifetime and performance**
- **First demonstrated steady operation of any pulsed electromagnetic thruster**

ELF-90 Current Status

A first of a kind, steady operating pulsed electromagnetic PPU developed and demonstrated

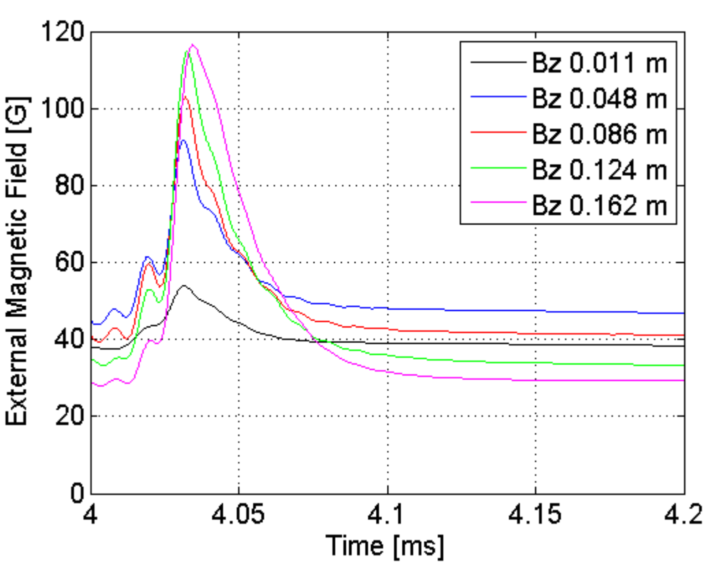


- Steady operation up to 5 kHz – 1E9
- Many propellant operated - Xenon, Argon, Nitrous Oxide, Water, Hydrazine
- Plume velocities 1000-4000 s Isp
- Discharge energies 0.1-3 Joules
- Excellent single discharge efficiency
- Wide power, performance scaling
- Lightweight, high thrust density system

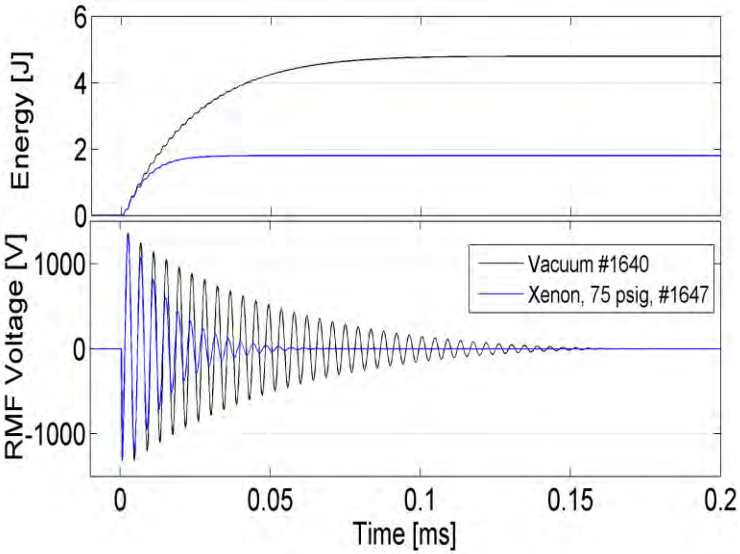
- Current challenges being addressed:
  - Thermal stability (1E5+ discharges)
  - High voltage, pulsed RF insulation
  - Gas utilization vs power scaling

Single Pulse Operation

1. Capacitor is charged to 1200 V
2. Switch is activated with <50 ns rise time
3. 1-4 kA current oscillates at 300 kHz, ionizing plasma
4. Increased effective plasma resistance loads the circuit, transferring power efficiently to the load
5. Plasma pressure ejects the FRC at high velocity, sweeping up background gas



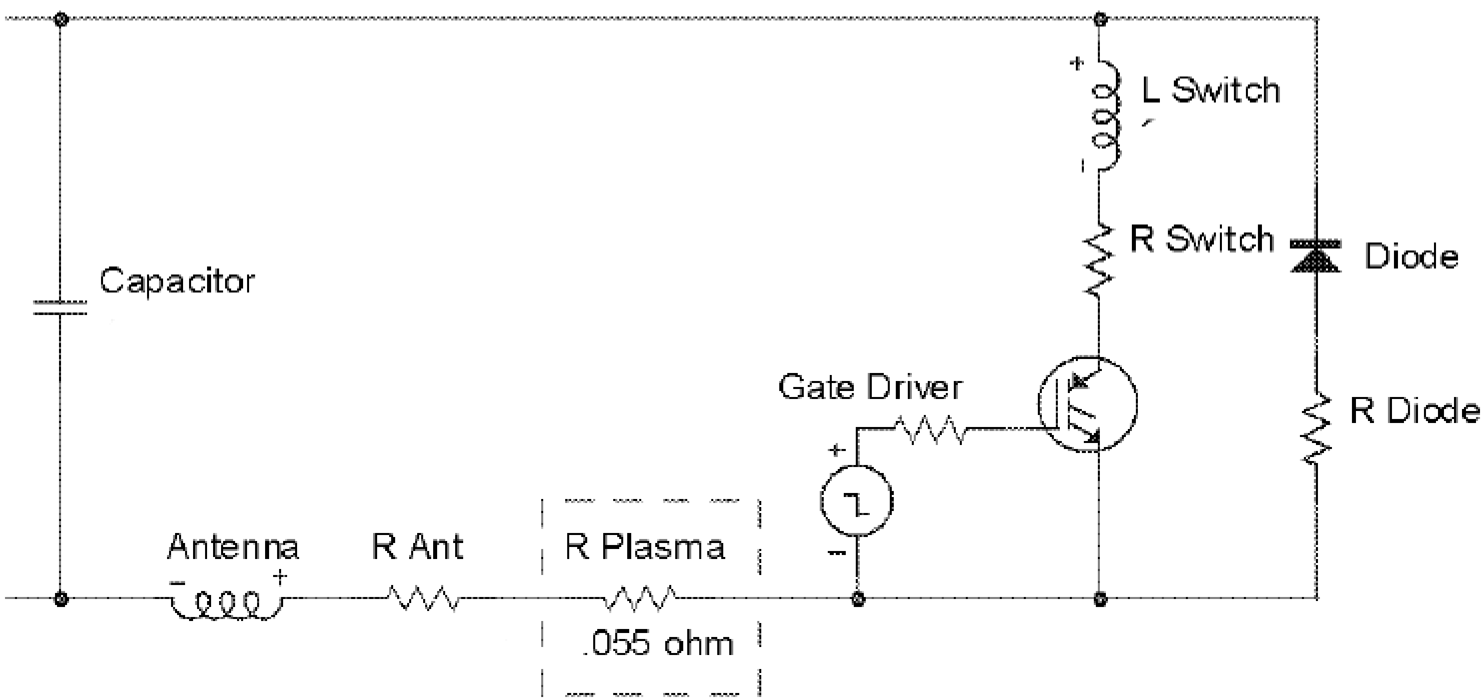
External magnetic field, showing a well-reversed FRC formation and translation.



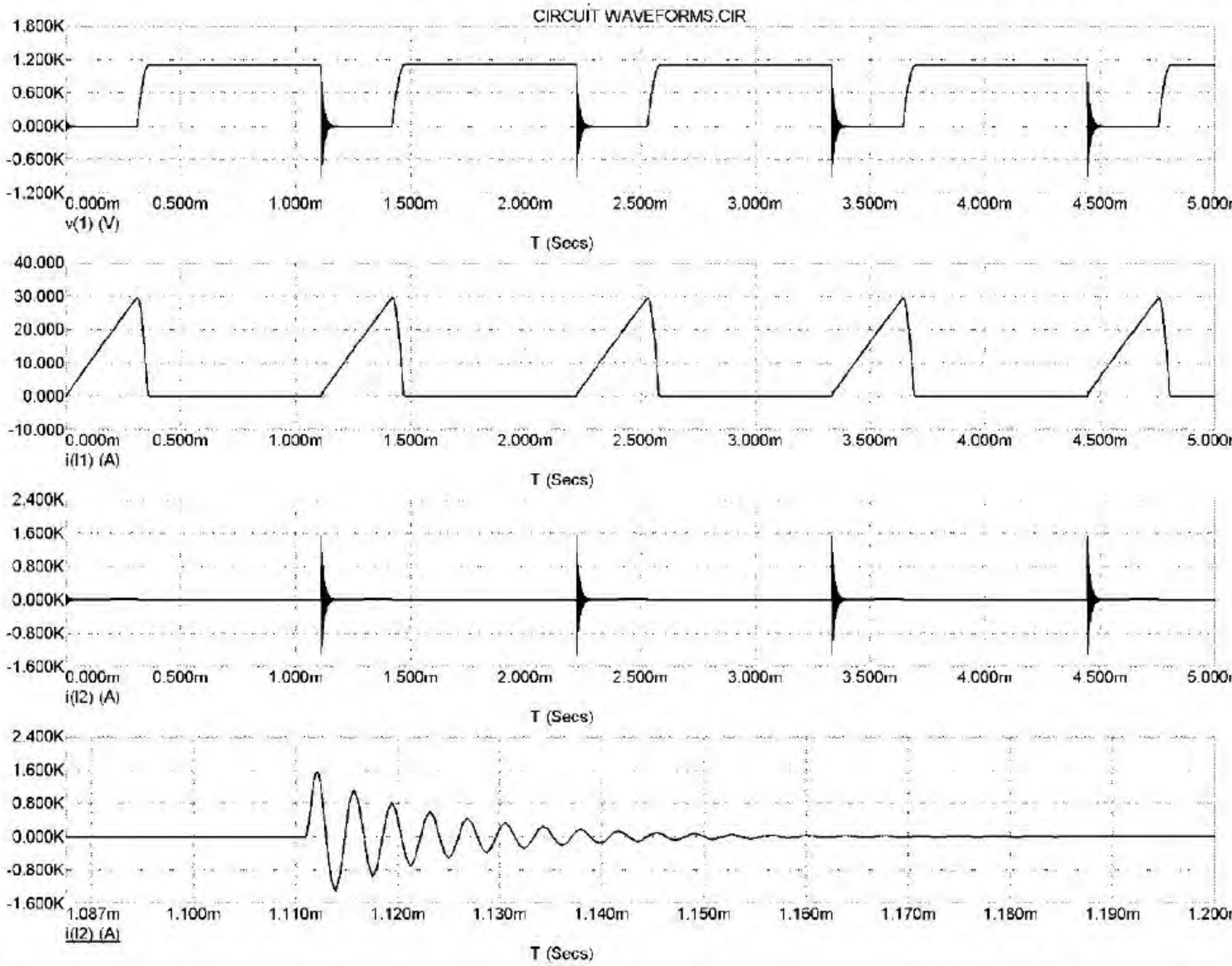
Singe pulse ringdown with and without a plasma

Generic Architecture

- Traditional design
- Two antenna phases oscillating at 300 kHz
- Resonant LC-circuit
  - High Q Capacitor is charged
  - High power semiconductor switch is triggered
  - Freewheeling diode yields steady oscillation
  - Crowbar diode yields exponential decay



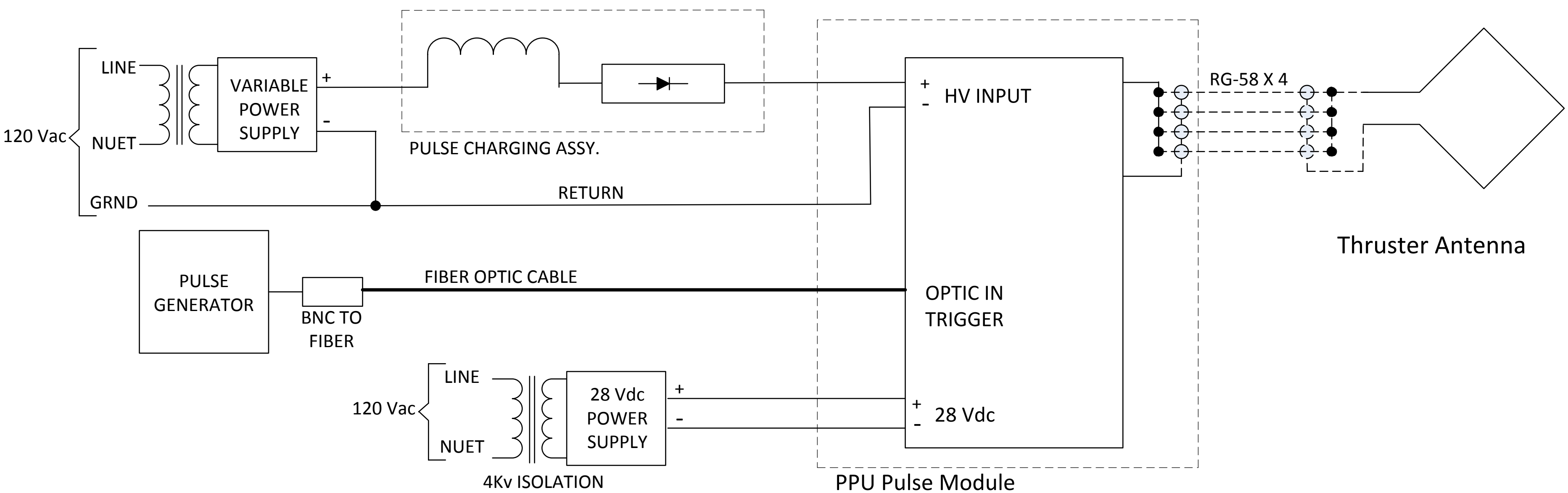
Steady Circuit Operation of a Pulsed Electromagnetic Thruster



Circuit simulation for a 1 kW steady operating thruster. Shown is a 900Hz charge rate with a 300 kHz RMF frequency. The first trace is capacitor voltage, second is battery draw, third is antenna current, with the last trace showing an expanded view of the antenna current.

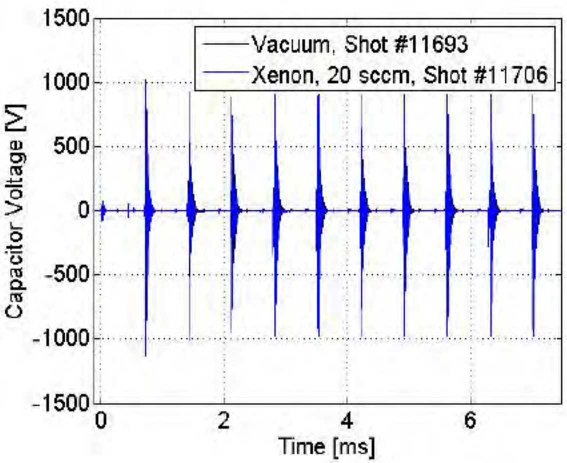
Architecture

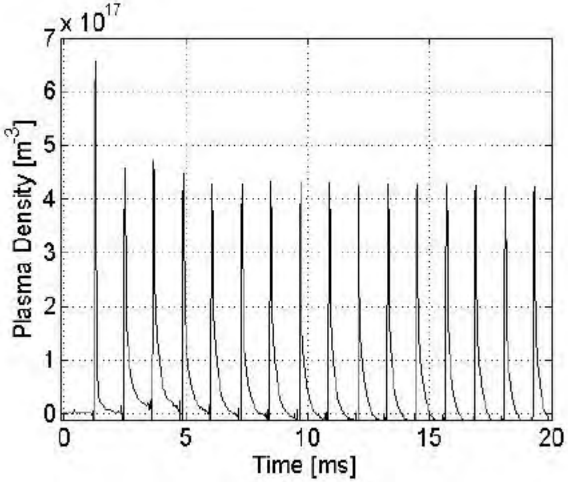
- Inlet power filter
- Inductive pulse charging
- Circuit protection
- Primary pulsed power
- Switch driver requirements
- Parallelization drives thermal, inductance requirements

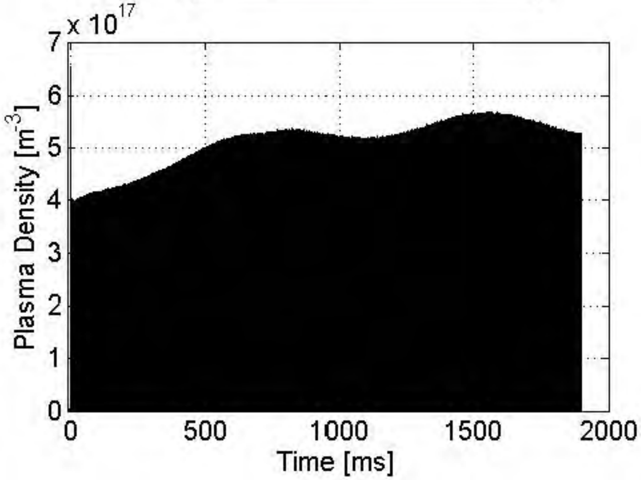


Steady Operation

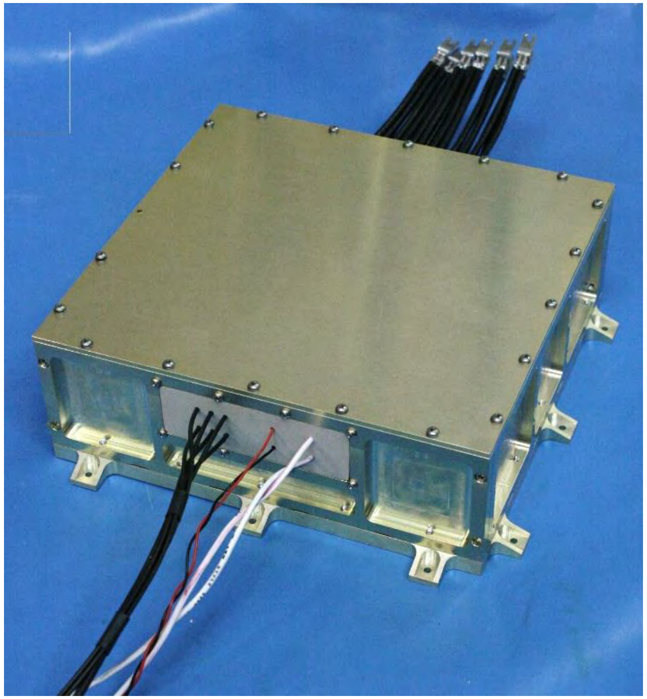
- Unlimited, steady operation of the PPU and thruster have been demonstrated
- Given sufficient, initial PI and steady flowing gas discharge formation and ejection is steady and repeatable
- Varying repetition rate (600-3000 Hz) and steady flow rate (2-50 sccm), thrust, Isp, and duration can be modified
- Clear thruster starvation and operation modes.
- Dangerously, the first 3 discharge are NOT representative of later discharges
- Same conditions can be achieved with different bias, flow, and repetition rate conditions







Enclosures



J6 Enclosure External

J6 Enclosure Internal

Vibration Testing Parameters

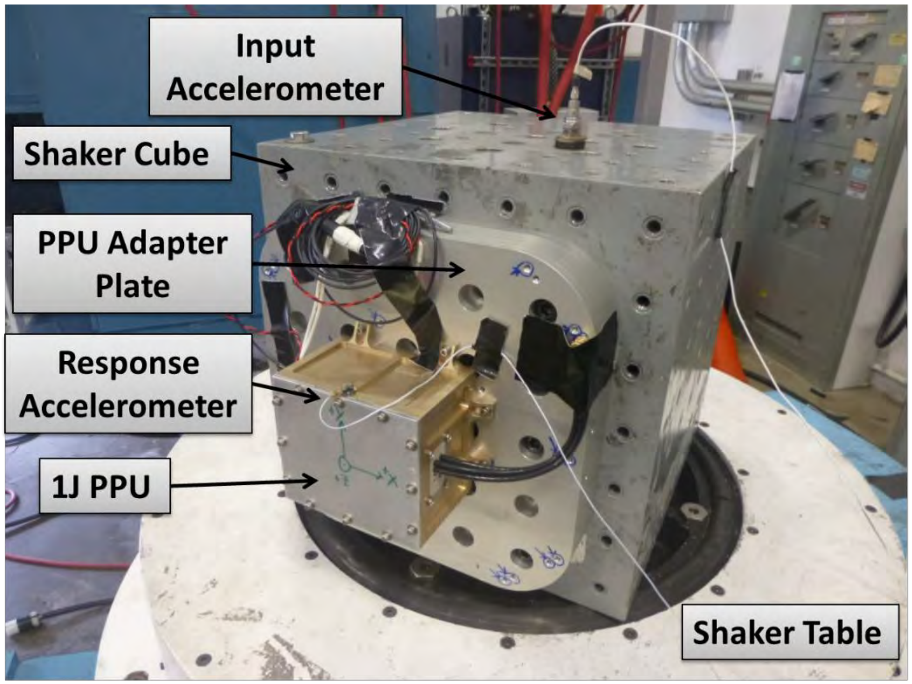
- The J1 and 6J PPU test articles
- An adapter plate for mechanical mounting to the shaker unit.
- The limited functionality testing cart including simulated ELF thruster coils, power supplies, triggering systems, cables, and an oscilloscope for measuring electrical outputs
- Cameras for photographing the configuration of the test articles prior to testing a given axis, and for video recording test behavior during random vibration and high-level sinusoidal vibration testing.
- The Vibration Test Facility shaker table, shaker cube, input and response accelerometers, and data acquisition system

Frequency (Hz)	ASD (g^2/Hz)
20	0.026
50	0.35
70	0.35
100	0.2
200	0.2
250	0.2
280	0.16
800	0.16
2000	0.026

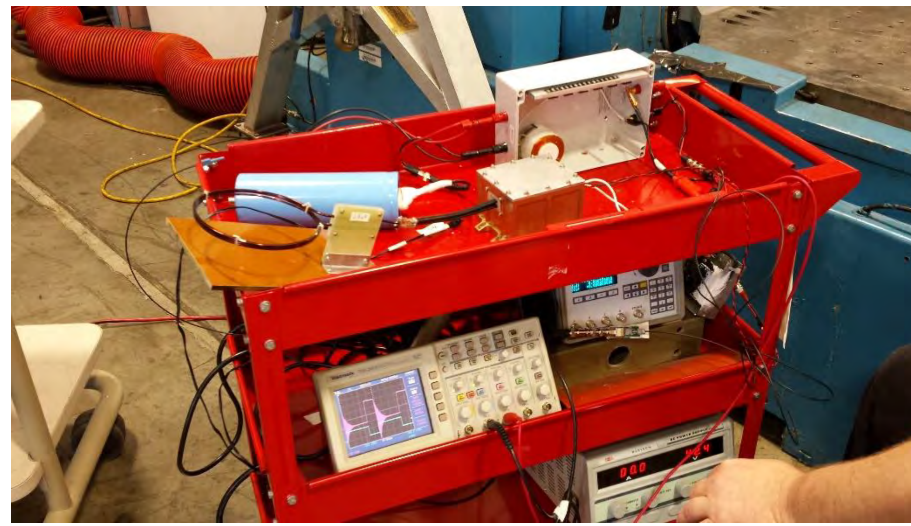
Combined vibration qualification standards

Vibration Testing

- Element Vibration Testing
- Altius, DARPA, AFRL testing standards

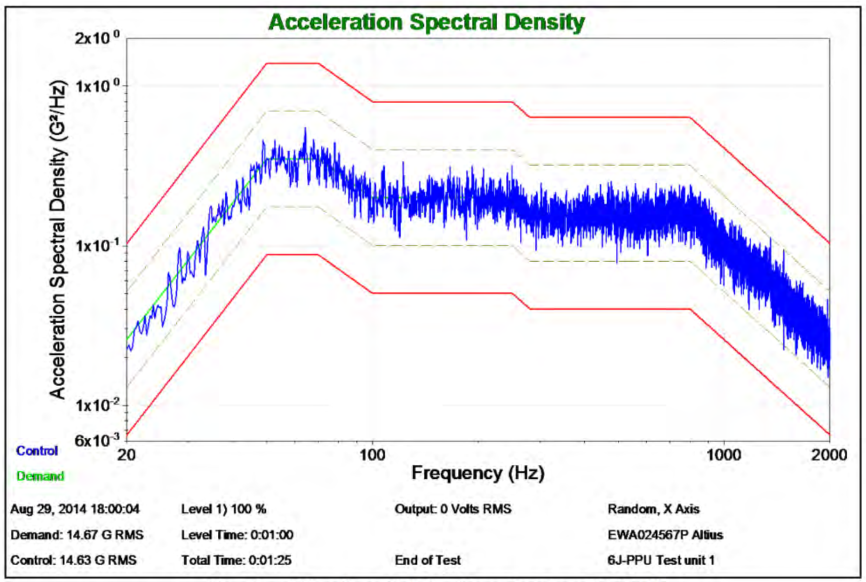


J1 PPU on Shaker Table Before Y+ Axis Testing

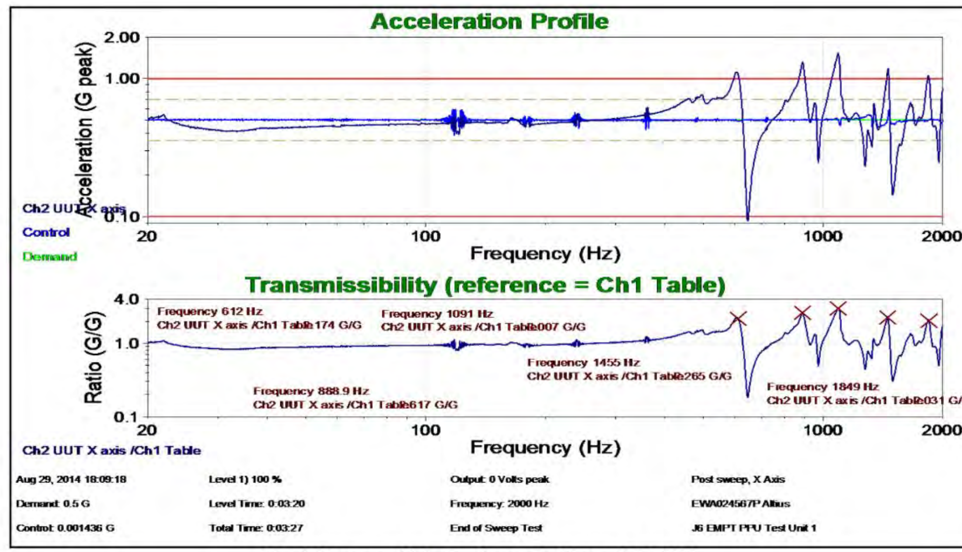


J1 PPU on the Limited Functionality Test Cart

NASA and AFRL Testing Standards



Random Vibration, X Axis, Sample Type 6J-PPU

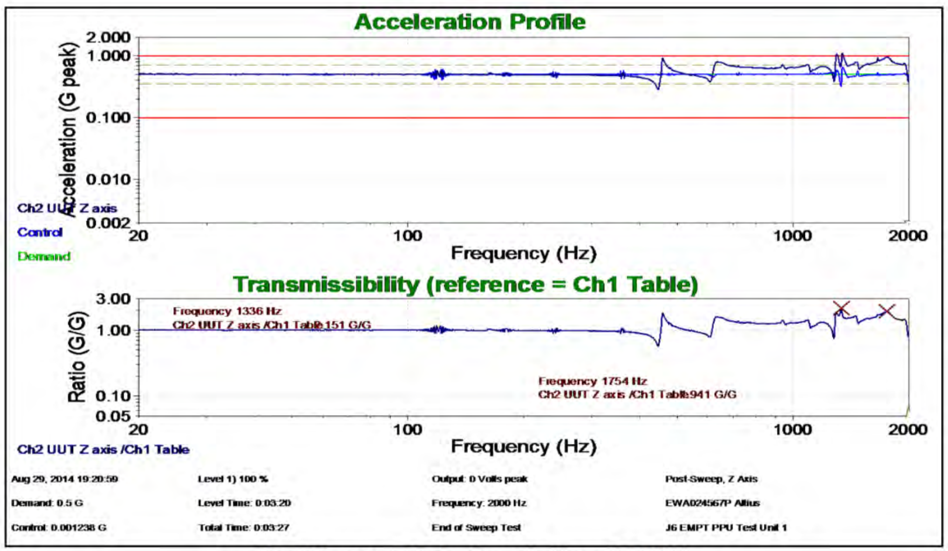


Post-Sweep, X Axis, Sample Type 6J-PPU

J6 PPU Vibration Testing Input Profile for all axes

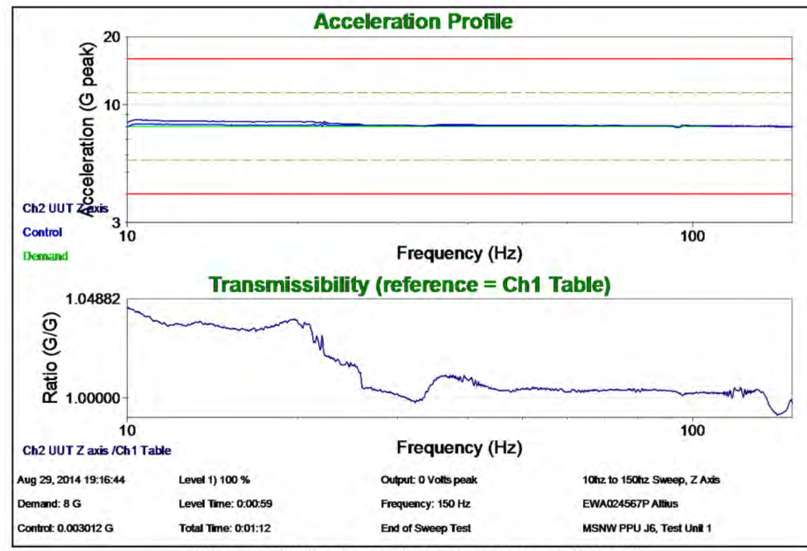
J6 PPU Vibration Testing Results - X Axis

Testing Results – Z axis



Post-Sweep, Z Axis, Sample Type 6J-PPU

J6 PPU Vibration Testing Results - Z Axis



Sinusoidal Vibration, Z Axis, Sample Type 6J-PPU

J6 PPU Vibration Testing Results - Z Axis

Conclusion of Vibration Testing

- The resonant frequencies for the two PPUs did not shift after random vibration testing and high-level sinusoidal sweep testing for any of the axes tested. This indicates no mechanical failures were caused by testing, and testing did not uncover any workmanship errors in spite of exposing the PPUs to vibration levels in excess of what is expected for flight on any of the launchers covered by the GSFC-7000A (GEVS) or EELV ESPA RUG standards.

- The boxes retained normal functionality after exposure to vibration test environments. The electrical performance had not noticeably shifted from the tests performed before the vibration testing.

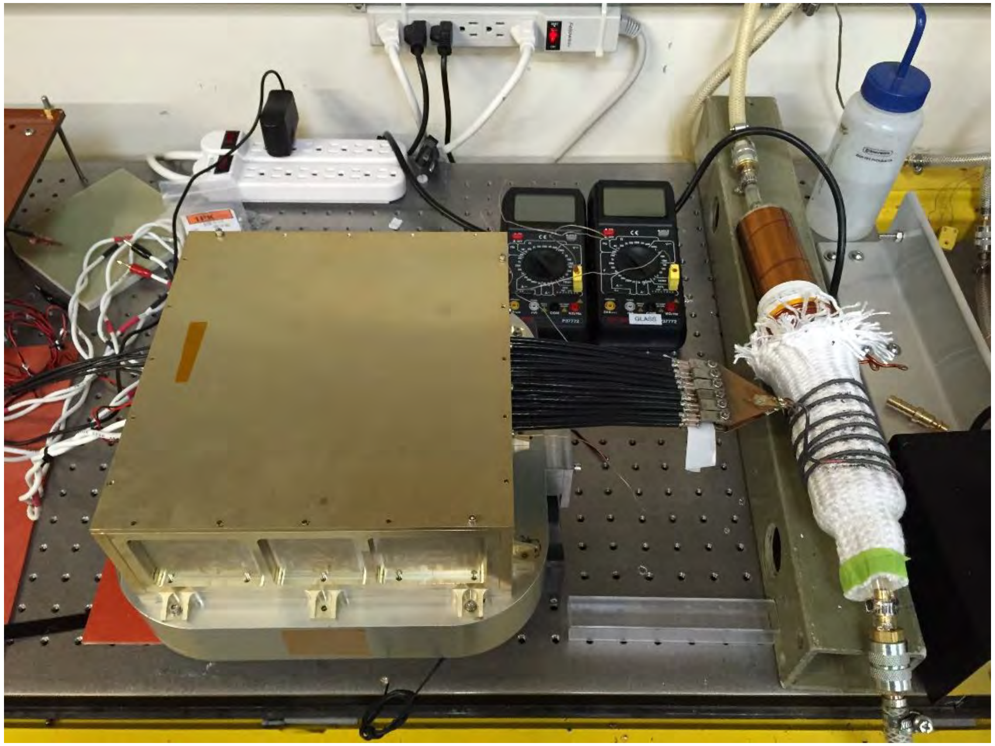
- While no modal analysis was performed to predict the first-mode frequencies of the boxes, the measured resonant frequencies were all greater than 600Hz, which should be more than adequate for space electronics enclosures. The test results indicate the enclosures built more robustly than is required for the application. The provides weight margins for future revisions of the PPU enclosure design.

- Based on the success criteria of:
    - Demonstrate the ability of the hardware to successfully operate after being exposed to the harsh launch vibration environment.

    - Uncover workmanship flaws such as loose fasteners or weak solder joints.

Thermal Characterization

- The cycle starts with the PPU powered-off, and the baseplate temperature held at 20°C long enough for the PPU internal temperature to stabilize.
- The PPU was powered-on at a constant input power as described in the following tests.
- With the PPU operating, the temperature of the baseplate was increased to the upper temperature limit (50°C).
- After the PPU's temperature has stabilized, the baseplate should was held at the upper temperature limit for one hour.
- After one hour of operations at the upper temperature limit, the PPU was powered-off, and then restarted once electrical circuits have been discharged, and an electrical Limited Performance Test (LPT) should be performed on the PPU.



Photograph of the fully assembled J6 Thermal Test Setup

Steady Thermal Response

Figure 1. Thermal image of pulse charging diodes

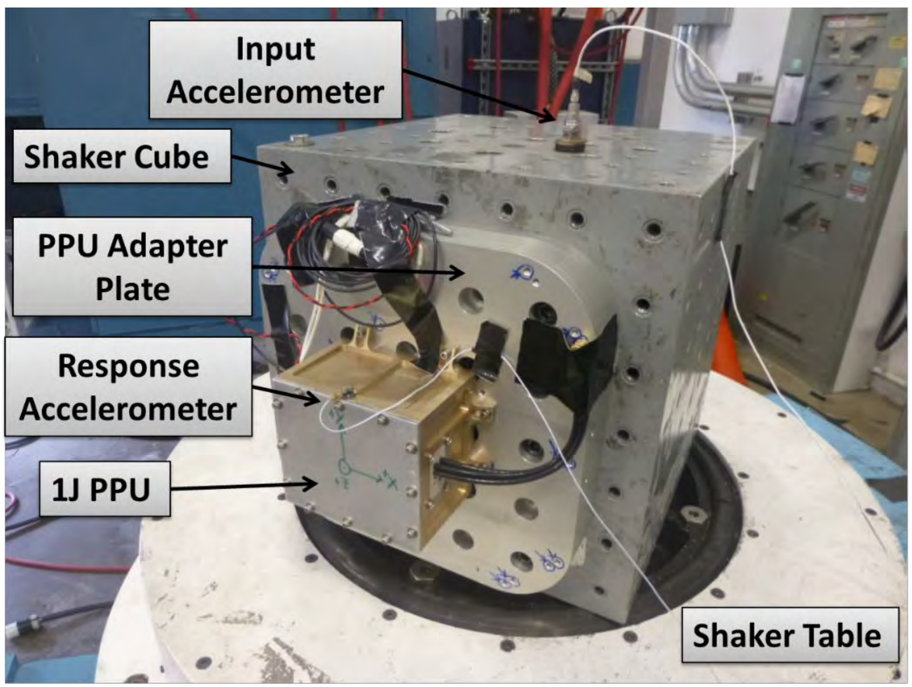
Figure 2. Thermal image of the the enclosure without the lid.

Figure 3. Thermal image closed enclosure and pulse charging diode and inductor.

Figure 4. Thermal image of the inductive plasma simulator.

Conclusions

Vibration and thermal characterization completed on 1 and 5 kW PPU



J1 PPU on Shaker Table Before Y+ Axis Testing

Figure 1. Thermal image of pulse charging diodes

Figure 2. Thermal image of the the enclosure without the lid.

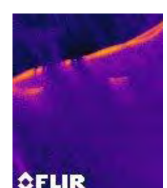


Figure 3. Thermal image closed enclosure and pulse charging diode and inductor.

Figure 4. Thermal image of the inductive plasma simulator.